INTEGRATING THERMAL TOOLS INTO THE MECHANICAL DESIGN PROCESS

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SUMMARY

The intent of mechanical design is to deliver a hardware product that meets or exceeds customer expectations, while reducing cycle time and cost. To this end, an integrated mechanical design process enables the idea of parallel process development (concurrent engineering). This represents a shift from the traditional mechanical design process. With such a process, there are significant issues that should be identified and addressed before re-engineering the mechanical design process to facilitate concurrent engineering. These issues also assist in the integration and re-engineering of the thermal design sub-process since it resides within the entire mechanical design process. With these issues in mind, a thermal design sub-process can be re-defined in manner that has a higher probability of acceptance, thus enabling an integrated mechanical design process. However, the actual implementation of such a sub-process is not always problem-free. Experience in applying the thermal design sub-process to actual situations provides the evidence for improving the sub-process, but more importantly, for judging the viability and feasibility of the sub-process.

INTRODUCTION

Integration of engineering analysis tools into computer-aided design/computer-aided engineering (CAD/CAE) environments is highly attractive since it holds the promise that the entire mechanical design process becomes concurrent. Such an integrated process enables the efficient overall evolution of a particular design. While design and analysis are conducted, machining paths for manufacturing, strategies for assembly, and plans for inspection can be developed. Automated finite-element modeling tools have supported this vision for quite some time. The ability to link finite-element modeling tools with (CAD/CAE) tools has been demonstrated for many applications, such as Auto Desktop, Pro Engineer, and I-DEAS Master Series. On the other hand, space-borne system-level thermal design (i.e., design beyond the part level) has not been available in an integrated environment without compromise or the penalty of a significant training effort.

The entire mechanical design process is composed of sub-processes such as configurational design, structural design, and thermal design. With increasing pressures on competitiveness and reduction in cycle time, it is necessary to redefine the system-level thermal design sub-process. The thermal design sub-process must strive to maximize the design activity and to minimize mundane, but necessary activities such as analytical model development. With the "big picture" in mind, re-engineering the thermal design sub-process should strive to globally optimize the overall mechanical design process.

The desired future state is an integrated mechanical design tool that has CAD/CAE, analysis, manufacturing, assembly, and inspection modules. CAD/CAE packages such as Pro Engineer and I-DEAS are striving to approach this ideal. However, it is fair to say that such an ideal for system-level aerospace applications is still several years into the future. The purpose of this paper is to describe the primary issues surrounding the integration of the thermal design sub-process into the entire mechanical design process, to suggest an integration approach that affords a higher probability of success, and to present lessons learned in exercising this integrated approach.

CONCURRENT ENGINEERING

First of all, it is necessary to clarify some terminology. Producing the "mechanical design" (from art to part) is the whole *process*. This process is composed of *sub-processes* such as design or analysis. Specific *activities* such as design assessment or testing are performed within each sub-process. The relationships between process, sub-process, and activity are shown in Figure 1.

The intent of a mechanical design is to deliver products that meet or exceed customer expectations, while reducing cycle time and cost. In reality, the final product is a mechanical system, where its compliance with requirements is measured against its system-level performance. However, in more traditional approaches the mechanical design has been developed by serial iteration with the various sub-processes (e.g., structural design, thermal design, and optical design). The demonstration of end-to-end system performance through analysis has been formidable in scope and protracted in time. In the face of budgetary (time and money) constraints, the ability to remain competitive is severely hampered with a traditional approach. Additionally, other sub-processes such as manufacturing, assembly, and inspection are deferred until the design matures. Again, this further increases the protracted lifecycle of a mechanical design.

In order to facilitate the mechanical design process, preliminary designs are analyzed with several idealizations. As the design matures, some of these idealizations are removed so that a more realistic representation of the actual performance can be obtained through analysis. There have been instances where serious design inadequacies have been uncovered late in the design life cycle. Such deficiencies could have been discovered earlier if the mechanical design process was more streamlined. The system-level nature of the thermal design sub-process is self-evident since thermal design issues permeate through most flight hardware. Compliance with thermal requirements is not the sole responsibility of the thermal engineer. From a system-level perspective, one of the primary thermal design objectives is to minimize consumption of system-level resources (mass, power, cost, schedule, etc.) within the given constraints. The ability to discover mechanical design deficiencies as early as possible increases the likelihood of developing a robust thermal design. Mechanical design deficiencies can be discovered not only in design development, but also in other sub-process such as manufacturing, assembly, and test. Lastly, today's competitive environment dictates that more design development be performed with less cost and schedule. Evolution of the thermal design sub-process is imperative since the traditional thermal design sub-process probably cannot meet more demanding cost and schedule constraints..

AN INTEGRATED MECHANICAL DESIGN PROCESS

An integrated mechanical design process permits the parallel development of the design, manufacturing, assembly, and inspection sub-processes. The emphasis of the design is at a system-level since each sub-process is concerned with the entire mechanical system. Obviously, a tool that assists an integrated mechanical design process is practically a prerequisite. Most importantly, the system-level performance can be more easily assessed, because problematic data interfaces between sub-processes would be seamless. Additionally, this would free the engineer from mundane or repetitive activities such as analytical model development or product database management to concentrate more on the creative design activity. To this end, CAD/CAE tools have incorporated many of the pertinent sub-processes such as analysis, manufacturing, and inspection. Some of the more familiar integrated CAD/CAE tools are AutoDesk, Pro Engineer, and I-DEAS Master Series.

Typically, engineers and designers spend an inordinate amount of time searching for and compiling product data. The cornerstone of the integrated mechanical design process is the product parameter database. This database is the complete mechanical description of the hardware product, which includes information such as the mechanical configuration, materials, mission design (orbital trajectory), and electrical power dissipation. A salient feature of this database is its comprehensive nature. Newly assigned personnel would have a single source for product information. The control of this database is typically a single authority, be it a single individual or a single organization. Database access is usually provided by a product database management system within the highly integrated tool. For ISO 9001 registered organizations, the documentation of design control would be very straightforward. Engineers and designers would have immediate access to the most current product data, virtually eliminating the need for local product databases.

As shown in Figure 2, the product database resides at the center of the mechanical design process. Sub-processes have ready access to the product database, and this permits each individual sub-process to be conducted in parallel. In the natural course of design, each sub-process may identify mechanical design revisions. If approved by the governing product database manager, each other sub-process owner is notified of the change and requested to assess the impact of the change on their sub-process. As stated earlier, sub-processes such as manufacturing and assembly can take a proactive stance by initiating their activities concurrently with the design and analysis sub-processes. Additionally, the design process lifecycle can be significantly reduced.

From a cursory glance, this proposed ideal process seems best suited for the detailed design phase, commonly referred to a "Phase C/D." However, this process can and should be used for earlier design development phases. The product database will lack some maturity, but an early assessment of system-level performance, especially with optical or radio frequency systems, should be established. This performance assessment also should include the ease of manufacturing, assembly, test, and inspection, sub-processes that are not usually addressed early in the design cycle.

Focusing on the thermal design sub-process, the most noticeable benefits are: 1) better access and control of most of the crucial thermal product data, 2) more widespread use of automated analytical model development, and 3) improved data interfacing with other sub-processes or sub-process activities. The underlying theme is improvement of sub-process efficiency which enables the thermal engineer to accomplish more design trade studies in a given time period (or to accomplish a given activity in a shorter time).

INTEGRATED MECHANICAL DESIGN ISSUES

While the benefits of an integrated mechanical design process are alluring, there are some major stumbling blocks that must be overcome. Even prior to exercising an integrated mechanical process task, some of these issues are readily apparent. For convenience, the issues are categorized as logistical and psychological. The logistical issues can be easily stated, and potentially solved with some definition of a process or procedure (similar to ISO 9001 documentation). However, the psychological issues are not easily resolved since the human mind is involved. The key to developing a solution to the psychological issues lies with understanding the mindset of the workgroup. One solution is to develop approaches that have a higher probability of being accepted and, ultimately, adopted. This concept is known as "ownership" or "buy-in."

Logistical Issues

1) Product parameter database accommodation for thermal design – a CAD/CAE configuration database tends to include a great deal of detail since it represents the actual hardware product. On the other hand, analytical thermal models are usually simplified, but faithful representations of the configuration. Configuration details such as number of fasteners or chamfered corners are typically inconsequential to thermal engineers. In addition, a plethora of such details makes the database unwieldy, difficult to work with, and hard to modify. Therefore, the CAD/CAE product database for the thermal design sub-process should include a simplified geometric representation of the hardware. It is this simplified geometry that will be the genesis of analytical models. The simplified geometric representation will be tailored specifically to the thermal design sub-process. Some coordination between the specific sub-processes (e.g., thermal and structural design) is required so that there are no technical data interface gaps (e.g., temperatures can be specified for all structural grid points).

The biggest issue is the development of a simplified geometric representation (sometimes referred as a "skeleton model"). One logical approach is to start with the detailed configuration and then modify it by removing and simplifying thermally unnecessary geometry. This requires proficiency with the CAD/CAE tool that the mechanical designer (not the thermal design engineer) usually possesses. However, the thermal engineer determines the degree of geometric simplification that is necessary and appropriate. The question is: "Who should develop the simplified geometric representation?" In an ideal situation, the thermal engineer would be skilled with the CAD/CAE tool, but in practice, the mechanical designer and the thermal engineer must work together to develop the simplified geometry. As both the designer and engineer cycle through the mechanical design process, they will begin to cross-train in the deficient areas

2) Data transfer to other sub-processes – It is highly likely that the thermal and structural analytical models will not be of the same fidelity. Mapping of temperatures from a relatively coarse thermal model onto a finer structural model has been a longstanding issue. There are some stand-alone mapping routines (refs. 1-3). In recognition of this issue, the integrated CAD/CAE tool should have provisions to handle this mapping procedure by integrating existing routines or by developing better ones.

3) Analytical thermal model size – The temperature mapping issue can be avoided by using the same fidelity as the structural finite-element model (FEM). Such models typically have many more nodes than the thermal model, sometimes approaching a few thousand nodes. Finite-difference solvers such as SINDA (refs. 4 and 5) have node and conductor limitations that are less than FEM solvers. Evolution of traditional thermal tools (e.g., SINDA) will be required to accommodate larger model sizes. If this does not occur, an opportunity for new FEM thermal solvers such as IMOS (ref. 6) may emerge. Troubleshooting and understanding results from large models have always been difficult. A portion of this issue is addressed by incorporating the ability to display temperature results graphically. Isotherms, themselves, do not provide the entire picture. Temperatures are merely the consequences of heat flow. Incorporating the ability to display the heat flow field is a necessity for interpretation of model results. The heat flow visualization option is not readily available from common FEM tools.

4) Analytical thermal modeling – With the use of FEM for thermal analysis, the modeling of thermal hardware such as louvers and closed-looped heater control become more difficult, if not impossible. The shear number of FEM grid points (or thermal nodes) will complicate the identification and simulation of thermal hardware.

5) Populating the product parameter database –Information is power, and this is very much the truth with the mechanical design process. The centralized product parameter database is a formidable body of knowledge. Constructing this database is huge task in itself, and facilitating the population the database is imperative so that the mechanical design process can be responsive. The issue of collecting and controlling product information is fundamental to this process.

In recognition of this problem, a procedure has been developed to expedite the collection of thermal-related product data (ref. 7). The procedure relies upon an intensive initial collaborative effort between senior thermal and systems engineers. The centerpiece of this procedure is comprehensive set of thermal design questions whose answers provide the basic structure for the thermal-related product data. Prior to the initiation of the pure thermal design sub-process, senior thermal and systems engineers complete the thermal engineering data survey to the best of their ability. It is expected that this procedure would take four to eight weeks depending on the system design maturity. Once the thermal design sub-process begins, the thermal design team will have an excellent point of departure. This procedure can be replicated for other sub-process so that the entire product parameter database can be assembled.

Psychological Issues

1) Sub-process "buy-in"— The integrated mechanical design process represents a major change in conducting business. People have a natural resistance to change. While it is quite easy to focus on the positive aspects, the real issue is at the working level. The engineers who will be implementing the integrated processes and sub-processes must be convinced that this change is sensible, appropriate, and necessary. To ignore a negative mindset is analogous to ignoring a design flaw until after the hardware is delivered. In this analogy, a tremendous amount of time and workforce is expended to fix the hardware. In the same manner, a tremendous amount of time and management energy late in the schedule will be expended if the integrated process is forced upon resistant working-level engineers. An integrated mechanical design process that is entirely new and abruptly adopted will probably meet a large wave of resistance, and ultimately its acceptance as a standard process will probably fail. Replacing an existing process with one that has no pedigree with the past casts doubt upon whether the previous process was appropriate at all. Additionally, a challenging burden is placed on the working-level engineers to quickly learn the new process and to produce real results. A more enlightened approach to change involves linking new processes with positive attributes from the previous processes. The working-level engineers should be involved in many of the aspects of the transition from the existing process to the new process. The idea is to obtain "buy-in" at the initiation of a new process rather than somewhere downstream.

2) Training engineers to become proficient with the process – Although this issue can be categorized under logistics, training is intimately related to "buy-in." It is very reasonable to expect a regimen of training. However, it rarely occurs in an effective fashion or in a sufficient amount. Again, involving working-level engineers in the planning and scheduling of training will help to define an effective regimen. Once initial training has commenced, a strategy for introducing the process into a production mode is required. The benefits of changing the process probably will not be realized in the short-term. In fact, the process change can result in higher cost and longer schedules which should be understood and accepted by management. Management needs to provide tangible evidence of endorsement. The strongest form of endorsement is to become familiar with the process by

participating in the same training. Other indications of management endorsement include providing separate labor funding for training, accommodating work schedule to facilitate training, and taking a long-term return-on-investment perspective.

THE THERMAL DESIGN SUB-PROCESS

Previous discussion has been centered on an ideal integrated mechanical design process. This ideal is far from standard practice in the current aerospace industry. Currently, there is no one CAD/CAE tool that may serve as an aerospace standard to support the integrated mechanical design process. Hence, the change from the traditional to the ideal mechanical design process should be a metered approach, using a series of steps to achieve the integrated mechanical design process. By understanding the gap between the traditional and ideal process and by taking stock in the identified issues, some decisions surrounding the integration of the thermal design sub-process can be established. Similarly, the thermal design sub-process will change commensurately with the mechanical design process (i.e., in carefully planned steps). Therefore, the first wave of change will align the thermal design sub-process with the ideal state. It is the first step in the thermal design sub-process evolution. While the ultimate goal is an integrated mechanical design process, the first objective is to develop a thermal design sub-process, which initiates integration and is likely to be adopted.

By examining the issues with the ideal mechanical design process, a great deal of insight can be extracted about the first step for the thermal design sub-process. The psychological issues are the most important ones. Even the most technically rigorous tool will be doomed for abandonment if the working level engineers do not truly believe that it is the "right" tool. Change is a self-realization process, and it would be highly arrogant to force-feed a new sub-process. Training is next in priority, and a sub-process that attempts to maintain some heritage with the previous sub-process will have a higher probability of acceptance (and ultimately gain "buy-in"). Most engineers would like to build on previous knowledge and experience, and recognition of this mindset is very important to defining an integrated thermal design sub-process. The logistical issues follow behind the psychological ones with regard to priority. This is not to belittle their seriousness or stature. Logistical issues can be defined in concrete terms, and so their solutions are more tractable than psychological issues. The top logistical issue is the development of the thermal "skeleton" database (geometry and other thermal-related product data). This is critical to the success of the integrated mechanical design process.

The proposed first wave of change for the thermal design sub-process spans the gap between traditional thermal tools and CAD/CAE tools. The "bridges" are translators that take a skeleton geometry and transform them into an analytical thermal model. Commercially-supported translators were selected to avoid any unnecessary tool development, and to relieve the burden of troubleshooting translator bugs. The foremost reason for such an approach is centered on the psychological issues. On the top of most thermal engineer's wish list is the automated development of an analytical thermal model. A thermal design sub-process that enables automated model generation and is still linked with traditional thermal tools has a high probability of acceptance. The training associated with this sub-process is focused on the automated model development. Obviously, there is no training involved with the thermal tools. Again, the training is not as formidable or protracted as an entirely new tool such as I-DEAS Master Series, and the possibility of sub-process use is higher than a totally new tool. Another salient feature with this sub-process is its independence from the specific type of CAD/CAE tool. The aerospace industry has yet to unanimously adopt a single CAD/CAE tool standard. Being independent from any specific CAD/CAE tool provides a great deal of flexibility in applying this sub-process in conjunction with other CAD/CAE tools. The skeleton geometry is preferably formatted using the IGES standard. However, other neutral formats such as DXF or NASTRAN can be accommodated. This reduces the amount of CAD/CAE tool proficiency that a typical thermal engineer requires. It should be noted that some basic CAD/CAE tool proficiency is required so that thermal-specific items such as thermal blanketing can be added to the "skeleton" geometry.

Figure 3 schematically depicts the thermal design sub-process. The product data is queried through a product data manager within the CAD/CAE tool. It is tacitly assumed that thermal-specific information such as the thermal blanket configuration has been added to the product data. The thermal skeleton database is extracted from the CAD/CAE tool and imported into a commercially-available, finite-element modeler, FEMAP (ref. 8). FEMAP was initially developed as pre- and post-processor for structural FEMs. With a graphical user interface (GUI), the user can construct an FEM, and after conducting the analysis elsewhere, the results can be graphically shown within FEMAP. Recently, upgrades were incorporated into FEMAP to permit the development of FEMs for thermal analysis. FEMAP is the workhorse tool of the thermal design sub-process. It is used to develop the FEM from the simplified geometry within the skeleton database. The FEM is developed using specific two- and three-dimensional elements (e.g., plates, laminates, membranes, bricks, and tetrahedra). FEMAP is not a "true shape" modeler; items such as cylindrical or spherical shells are approximated with plates. Additionally, the thermophysical properties such as thermal conductivity and specific heat as well as mechanical properties such as density are prescribed. Variable thermal conductivity and/or specific heat can be accommodated by FEMAP. Heat loads from internal power dissipation may also be assigned. These attributes assist in the determination of the thermal math model (TMM). The thermo-optical properties are assigned and doubly-active geometry is identified for the development of the geometric math model (GMM).

From FEMAP, TCON (ref. 3) can be used to develop the input files for the traditional thermal tools. This commercially-available tool was developed under a small business innovation research grant with the Goddard Space Flight Center. TCON is a translator that imports the FEMAP data and creates a TMM and a GMM based on the finite-element grid. This usually includes node and conductor definition, array specifications if there are variable thermophysical properties, and SINDA execution control constants such as absolute temperature scale, solution routine, and convergence criteria. The user must incorporate any variable logic and output options. There is flexibility to create a SINDA/G (ref. 4) or a SINDA/FLUINT (ref. 5) formatted TMM.

In most space-borne thermal designs, it is necessary to develop a GMM to determine overall radiation interchange within the TMM and to calculate absorbed environmental heating (i.e., direct solar, planetary albedo, and planetary emissive). Once the FEMAP data has been imported into TCON, a GMM that contains the entire geometry can be generated. At this time, it is not possible to distinguish "internal" geometry from "external" geometry. Separation of internal and external geometries must be performed manually. TCON can generate a TRASYS (ref. 9) or a TSS (ref. 10) formatted GMM. In this particular thermal design sub-process, TSS is the preferred thermal radiation tool because of its use of the Monte Carlo ray-tracing and GUI features.

Once the GMM and the TMM have been generated, the specific thermal tools (i.e. SINDA/G or SINDA/FLUINT and TSS) are used to perform the analysis. TCON generates output logic to create an ASCII temperature output file that may be imported into FEMAP. Within FEMAP, the isotherms are graphically presented. The MAPBACK routine within TCON permits the mapping of temperature results onto the structural FEM. The thermal and structural FEM grids do not need to be equivalent. The mapped temperature file can be readily used by a structural analysis tool such as NASTRAN.

LESSONS LEARNED

The Goddard Space Flight Center developed the path between FEMAP and the traditional thermal tools. The work described herein has linked FEMAP and the product data. This proposed thermal design sub-process has been used for a few thermal design activities, and the experience has been invaluable in identifying the capabilities and limitations of this sub-process.

The initial roll-out of the thermal design sub-process was hastily prepared. While there was buy-in at the management level, the sub-process was imposed on the working-level engineers without sufficient training. As one can imagine, there was a sundry of problems. Because the thermal skeleton geometry had not been developed, importing the product data into the FEM tool was arduous and frustrating. The working-level thermal engineer struggled with the FEM meshing, because of the lack of training. Additionally, the resulting TMM was too large for the capability of SINDA/G. When the thermal skeleton geometry started development, the CAD/CAE designer was distracted with other activities, and the skeleton geometry was never completed to the satisfaction of the thermal engineer. In short, the initial roll-out was a dismal failure since implementation of the thermal design sub-process was not well-thought out.

Shortly afterward, a small thermal team was formed to receive some training and to put the sub-process through some trial cases. This team was formed with thermal engineers with a keen interest in this sub-process. At the same time, an upgrade to FEMAP was released, which had improved IGES translation capability. Some classroom training for FEMAP and TCON was conducted, and the link between FEMAP and the traditional thermal tools was established for the first time on a working level. Rudimentary thermal analysis problems (e.g. insulated flat plate in

Earth orbit) were undertaken and were validated with hand-calculations. The team generated a preliminary thermal design sub-process primer (ref. 11) for other thermal engineers to consult.

The next usage of the sub-process demonstrated some success. An avionics support structure (X2000 Integrated Avionics Structure) was analyzed to assess the benefit of using composite materials versus aluminum. The product data was imported into FEMAP, and the geometry was translated as "solids." The working-level thermal engineer did not have the proficiency to mesh the solid geometry. At this point, it is not clear whether solid geometry can be meshed for thermal modeling purposes. However, there were discrete geometry points, and these were utilized to create the thermal FEM within FEMAP. In turn, the SINDA/G model was easily created. This model was a conduction only TMM, and a GMM was not required. The results for the aluminum structure are shown in Figure 4. As noted previously, the development of the thermal skeleton geometry is a must for this sub-process. Additionally, the need for the CAD/CAE designer and thermal engineer to interact in the definition of thermal pertinent product data was shown clearly in this case.

During the same time the avionics support structure analysis were underway, an inflatable radio interferometry antenna (the Advanced Radio Interferometry Between Space and Earth, ARISE) thermal analysis was being conducted. This was the first full use of the thermal design sub-process since the analytical determination of the interferometric performance was derived from thermostructural distortion analysis. Due to the preliminary stage of the project, the product data had not been formally established. However, a structural FEM had been developed. Through discussions with the structural engineer, the applicability of the structural FEM for thermal modeling was established. It was determined that small modifications such as ignoring the vacuum-deposited aluminum layers on the reflector were required. These changes were implemented with FEMAP and SINDA/FLUINT TMM was easily created. However, the structural and thermal FEMs maintained a one-to-one grid point correspondence. One salient feature of TCON is its ability to always generate positive conductance values. When triangular elements are generated, negative thermal conductance will result when one of the triangular interior angle is greater than ninety degrees. However, TCON recognizes this situation and employs a different, but rigorous method to determine the thermal conductances.

The generation of the antenna GMM proved to be more difficult. A number of TCON bugs were uncovered when translating the FEM to a TSS GMM. Most of them were minor, for example the declaration of the initial conductor, an option not used for the GMM, but required for completeness, was not specified. The most serious bug was the incorrect translation of a trapezoid. The TCON vendor eventually solved all the identified bugs, but the GMM development took longer than expected. The size of the TSS GMM was at the maximum capability of TSS. System memory was nearly depleted during a TSS calculation, and the size of temporary files nearly depleted available hard disk space. The oversight occurred in the assessment of the structural FEM for thermal analysis use. Even though, the number of FEM grid points was modest (~500), the number of GMM surfaces created could increase by an order of magnitude. This is because a thermal node (i.e., FEM grid point) is made up of portions of all surrounding elements (e.g. in a rectangular mesh, each node can be surrounded by four element, implying four separate GMM surfaces). The resulting TSS GMM for this antenna had nearly 3600 surfaces. Fortunately, radiation interchange factors and absorbed environmental heating were computed successfully.

The antenna system isotherms when positioned at the sub-solar are shown in Figure 5. FEMAP was used to transport these results to the structural model. The thermostructural distortions were determined and subsequently so was the interferometric performance.

CONCLUSIONS

This proposed thermal design sub-process is the first step in evolving toward a truly integrated mechanical design process. As demonstrated previous, the proposed sub-process is still in the incipient stages of usage, and some pitfalls have been uncovered. At the same time, this sub-process has shown promise for its use on component- and system-level. Over its short life span, there has been many lessons learned. The key to its subsistence is buy-in from the working-level engineers. Since FEMAP has its heritage with structural design and analysis, most thermal engineers indicated that FEMAP is not organized from a thermal design and analysis perspective. The FEMAP, TCON, and SINDA/G vendors are currently considering a collaborative effort to integrate this tool suite. The development of the thermal skeleton geometry remains an major open issue.

This proposed thermal design sub-process was developed by understanding the underlying logistical and psychological issues of an ideal mechanical design process. It is likely that the ideal mechanical design process will continue to evolve with time, so the thermal design sub-process will need to evolve as well. The identification of the ideal mechanical design process issues will dictate how the thermal design sub-process evolves. Integrated mechanical design tools that were presently dismissed should be monitored so their future benefit may be known. Other efforts such as the Standard Exchange for Product Data (STEP) should be closely watched for its possible incorporation into the integrated mechanical design process.

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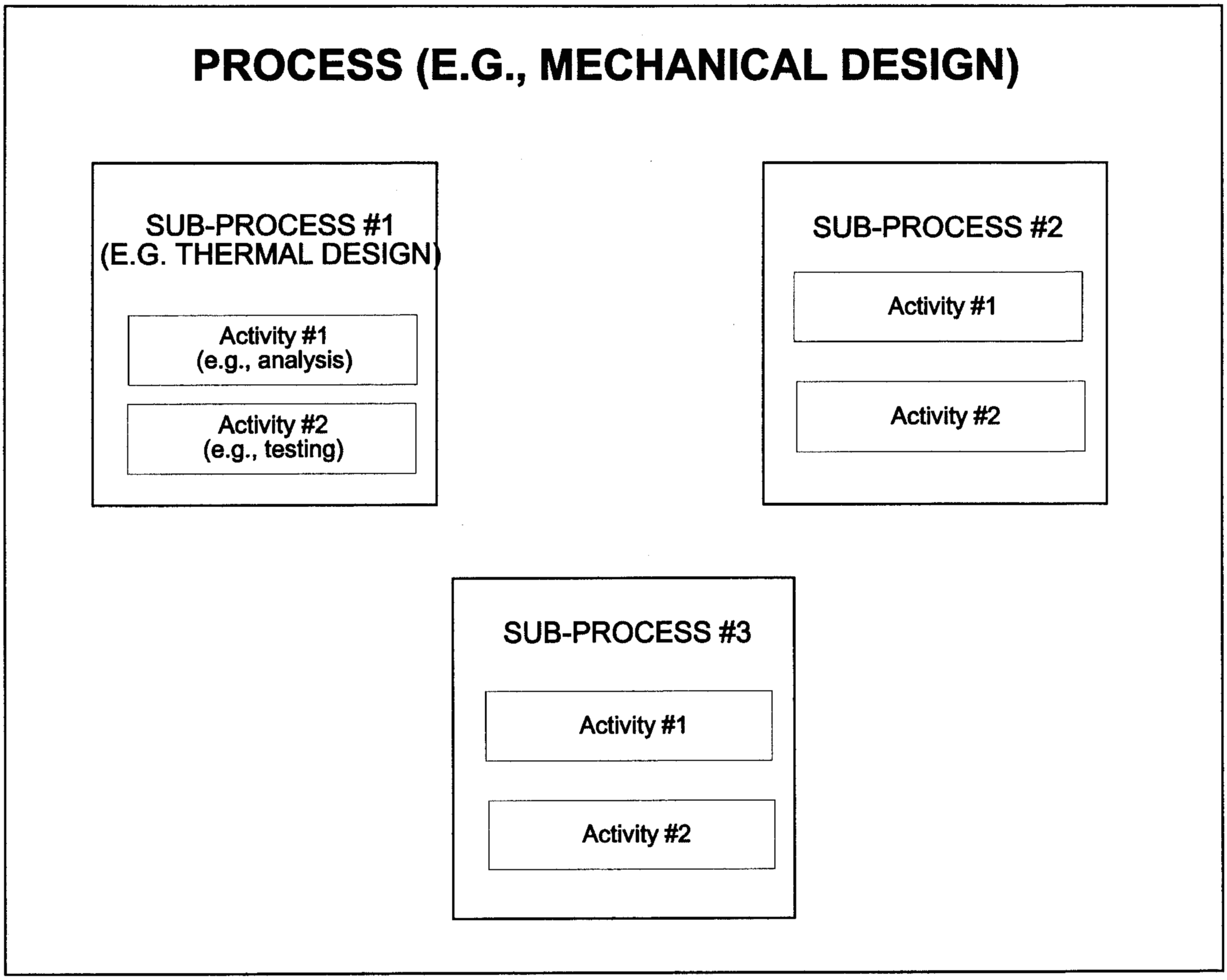

Figure 1 - Relationships between process, sub-process, and activity

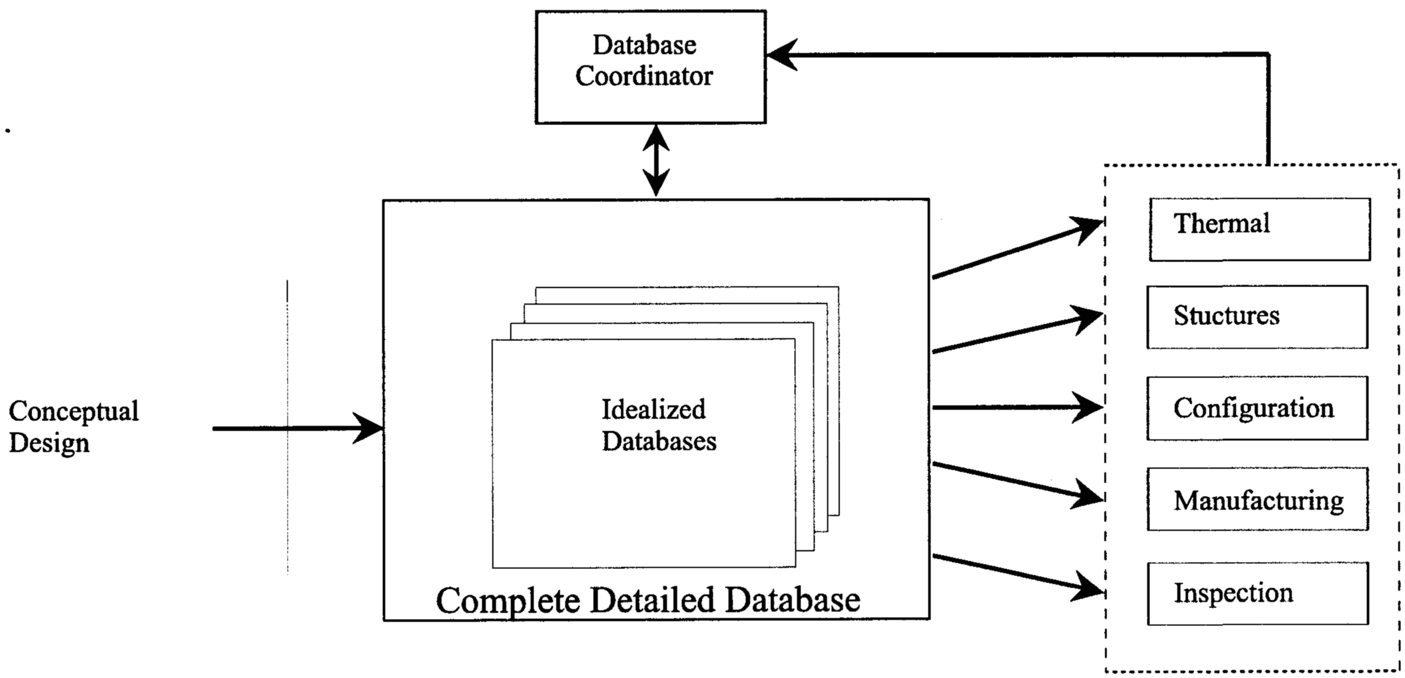

Figure 2 - The product database and its relationship to other sub-processes

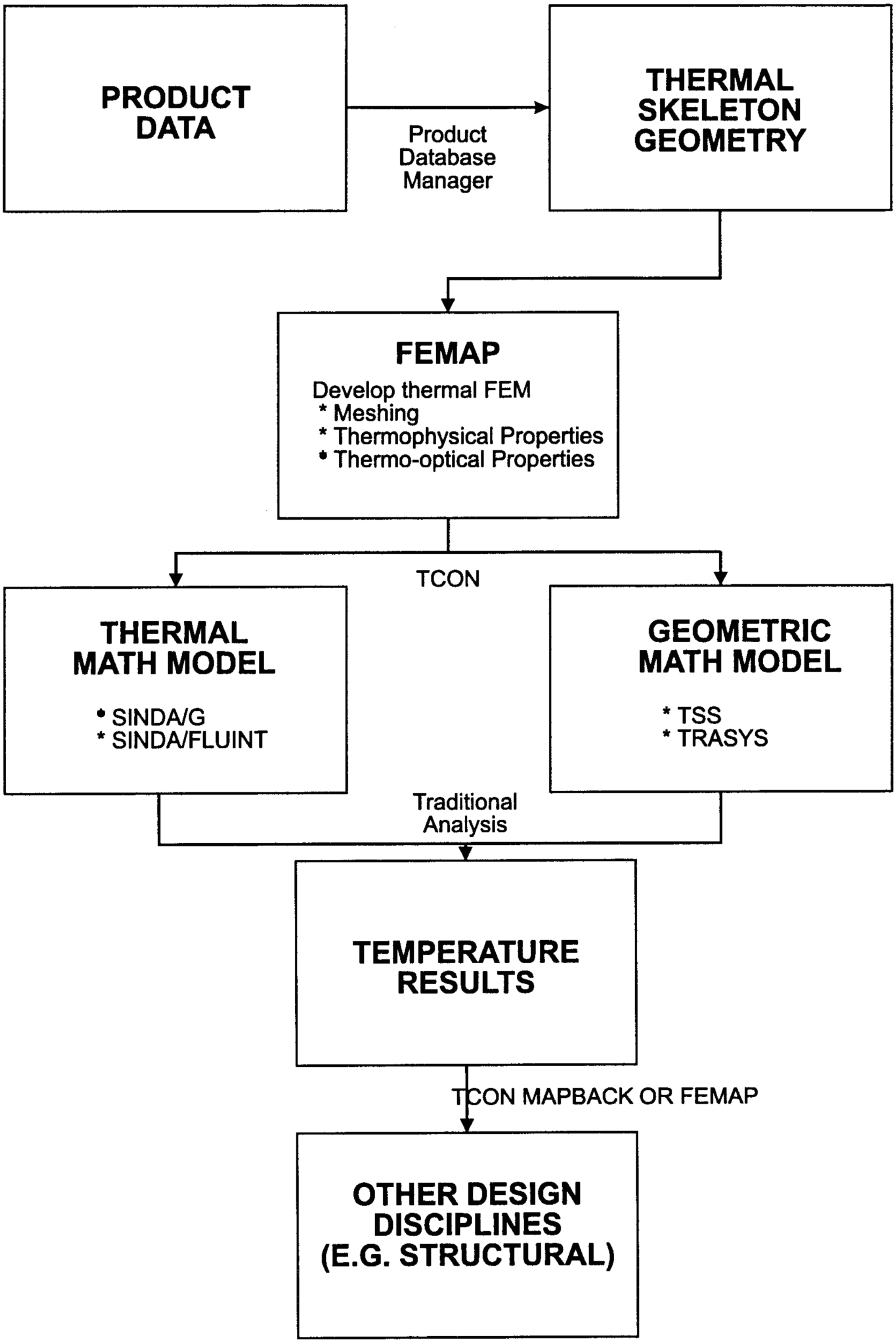

Figure 3 - Integrated thermal design sub-process flow diagram

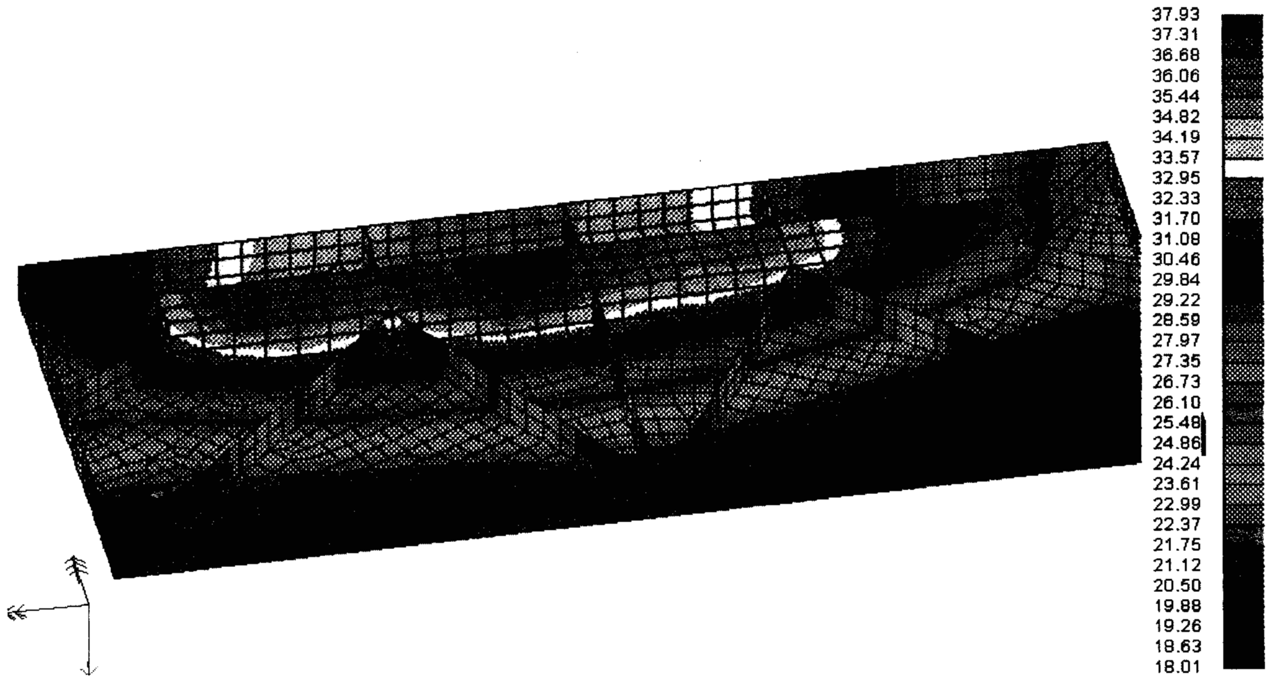

Figure 4 - X2000 integrated avionics structure temperature contours

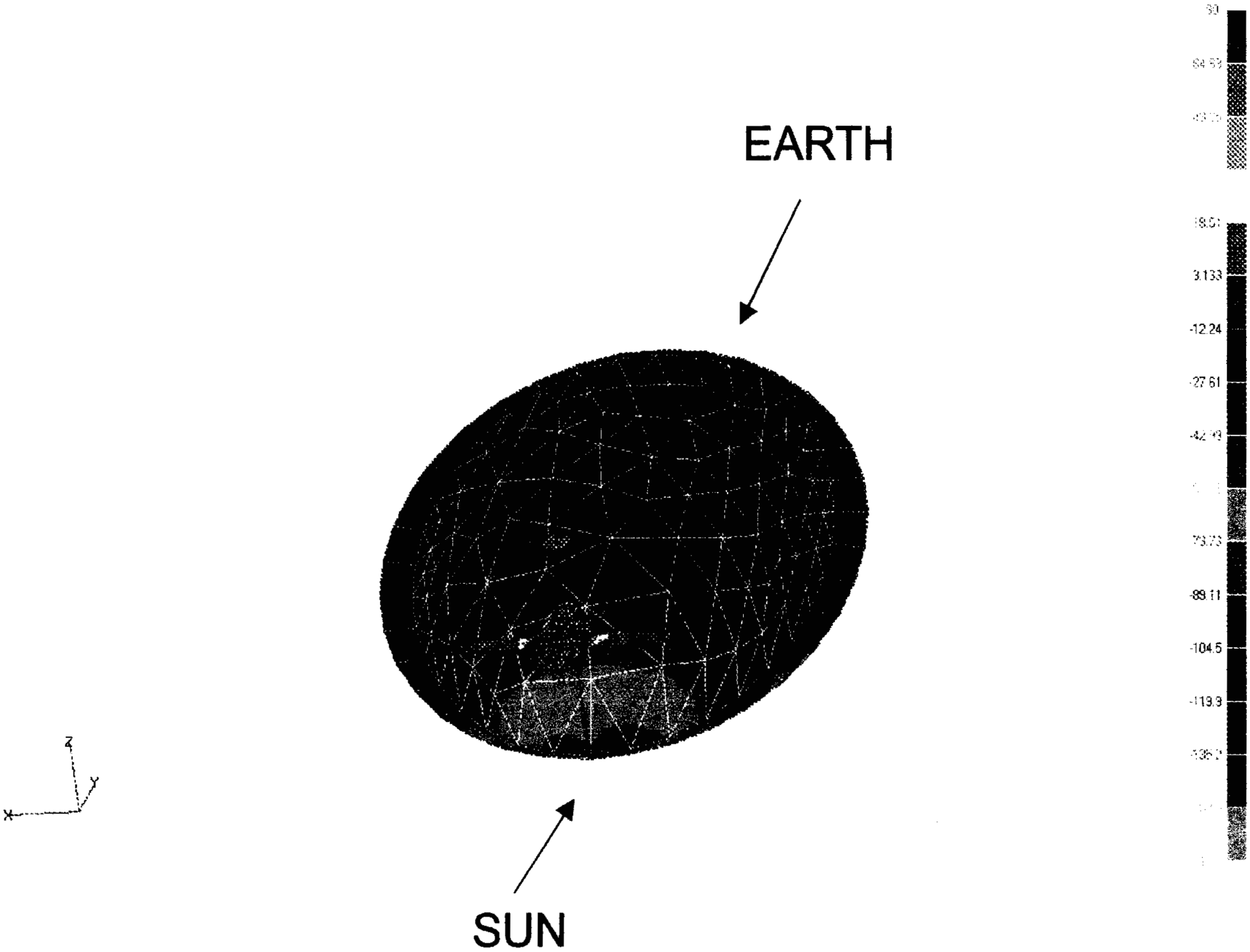

Figure 5 - Inflatable antenna flight system (ARISE) temperature results at the sub-solar point